M. Fanelli, G. Giuseppetti, A. Castoldi, P. Bonaldi

Dynamic characterization of Talvacchia dam: experimental activities, numerical modelling, monitoring

report presented at the *10th Word Conference on Earthquake Engineering*, Madrid, July 1992

ABSTRACT: The multi-annual experience relevant to static and dynamic analyses and measurements carried out on Talvacchia arch-gravity dam have allowed to achieve a deep knowledge of the structural behaviour and the setting-up of numerical models calibrated on experimental data.

In addition to a static, monitoring system installed to measure cause and effect quantities, a dynamic campaign, lasted more than three years, has been executed.

During this campaign, the dam has been excited twice a day by a suitable mechanical exciter (vybrodine) and the dynamic characteristics of the structure, in terms of eigenvalues and eigenvectors, have been measured. A correlation between the environmental variations and the structural dynamic response has been established.

Using such an amount of data several mathematical models have been calibrated and validated.

1. INTRODUCTION

For a number of years now a widespread research programme, promoted and financed by ENEL and based on the collaboration between ENEL CRIS and ISMES, has been carried out with the intention of studying the seismic behaviour of concrete dams.

Within this programme, in situ forced vibration tests to determine the actual dynamic behaviour of the structures have been carried out, mathematical models and computation instruments have been set up.

So far, about 40 dams have been subjected to forced vibration tests; as an example, in fig. 1, for different kind of dams, are plotted the natural frequencies of the 1st antisymmetric and the 1st symmetric modes (multiplied by height H of the dam to account for dam size) versus the ratio between crest length and dam height (this ratio representing the "shape factor" of the structure).

2. AIMS OF DYNAMIC SURVEILLANCE SYSTEM

The on-going evolution has led to a substantial extension of the tasks assigned to surveillance systems, with the aim of achieving an increasingly comprehensive knowledge of the seismic event and of the various effects on the dam.

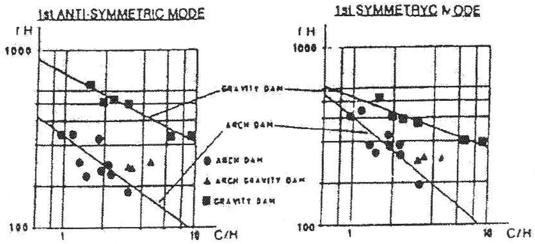


Figure 1. Correlation between experimental results and geometric parameters.

The most immediate and indispensable objective obviously continues to be that of signalling the quake and its characterization in quantitive terms, with the determination of intensity, epicentre distance and so on, and with the recording of the accelerograms at the base and along the abutments.

In recent years, there has been a further extension in the objective of monitoring systems. In fact, besides

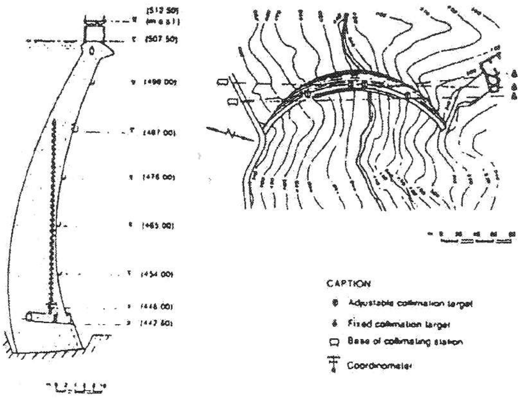


Figure 2. Talvacchia dam

the recording of the quake and the structural response, these are meant to enable also the identification of possible damages inflicted on the structure. Such identification is essential to facilitate the immediate and complete start-up of the plant. The dynamic parameters significant in the context are the modal ones: natural frequencies, modal shapes and damping. Their determination involves a complex data processing problem, which generally starts out from the knowledge of the input-output type relationships, where the output is represented by the response of the dam and the input is an excitation factor of some kind. For this purpose, use may be made of either a natural excitation (provided, for instance, by the local microseismic activity) or else, in the interest of greater accuracy, an artificial excitation like the one generated by mechanical vibrators.

A final item to be bourne in mind is that the installation of a surveillance system always incorporates the aim of obtaining data on the actual behaviour of a dam under high loading conditions, data that cannot be obtained otherwise.

Their availability is the sole means for gaining an understanding of complex phenomena set up during a quake, these being for instance:

- foundation-structure-reservoir interaction;
- energy dissipation;
- influence of the non-linearities, so as to facilitate confirmation of the computation codes. In these terms, the surveillance system also becomes an effective tool for basic research.

3. THE SURVEILLANCE SYSTEM OF TALVACCHIA DAM

Within the basic research programme described in par. 1, in 1986 a new phase was initiated, the aim being the design of a seismic surveillance system capable of meeting the general criteria set out above.

An initial example of this system was installed on the Talvacchia dam (see fig. 2), which is located in the vicinity of the city of Ascoli Piceno in Central Italy, an area with moderate seismic activity.

This arch dam (height 77 m, crest arc length 226 m, reservoir capacity 14 million cu meter), has already been the object of several investigations, both theoretical and experimental: in particular, forced vibrations tests were carried out in 1972.

Setting out in greater detail, the aims underlying the installation of the new dynamic control system were as follows:

- to execute automatically and periodically forced vibration tests and measuring the structural response over a long period of time, with varying external conditions (water level and ambient temperature);
- to acquire the values of static quantities that make up an index of the general behaviour of the structure and which at the same time may have a determinant influence on the dynamic behaviour;
- to record the seismic events that could involve the dam, when their intensity exceeds a pre-established level.

3.1 Static monitoring system

In the initial configuration of the static monitoring system, the main instruments installed were the following:

- direct plumb-line located in the main cross section;
- collimation;
- thermometric network embedded in the concrete, both in the main cross section and in two lateral sections;
- external thermometers to measure air and water temperatures;
- dilatometers to measure the opening of the joints;
- clinometric network;
- devices for measuring leakage and uplift pressures.

It is worth while noting that in 1966 an analogical processor was installed with the first static deterministic model for the control

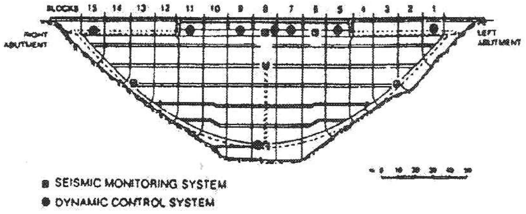


Figure 3. Location of the seismometers and accelerometers.

of the structural behaviour. This installation represented the first example on an Italian dam.

In 1973 the static monitoring system was improved by the installation of an automatic collimator and by the automatization of the plumb-line readings and the temperature measurements.

In 1986 the system was completely automatized and centralized (see fig. 3). The availability of pluri-daily measurements has allowed a better calibration of the deterministic model. A more correct interpretation of the structural behaviour and a greater reliability of the forecasting model to be used for the on-line safety control was then possible.

3.2 Dynamic and seismic monitoring system

In 1986, together with the improvement of the static monitoring system, instruments for the recording of the dynamic behaviour and seismic response of the structure were installed.

The dynamic control system was installed for measuring the dynamic behaviour of the structure under the changes of environmental conditions (storage level and ambient temperature). To this aim two forced exitation tests were automatically carried out every day (frequency range 3 to 11 Hz) for a period of more than three years.

Such dynamic control system was composed of the excitation system to generate the forced vibrations and the instruments network to monitor the structural response.

The excitation system is made up of an eccentric mass mechanical exciter, tied to the structure at a height of 505 m (see fig. 3); the selected position is suitable for exciting both the symmetric as also the antisymmetric modes.

The main characteristics of the exciter are:

- maximum force	50 kN;
- frequency range	0.1-11 Hz;
- overall weight	6 kN;
- power	1.6 kW

The instrumentation network is made up of a network of 10 sismometers.

The choice of this type of transducer was dictated its sensitivity, which enables it to measure with a high degree of precision the small vibration amplitudes generated during the forced tests.

For containing the cost of the system, the measurement of the response motion was limited to eight sismometers on the crest arch - seven deployed in radial direction and one in the tangential - and to two additional instruments in the radial direction along the central cantilever (see fig. 3). With this minimum set-up it is possible to identify with certainty the modal shape of the first vibration modes.

The choice of the positions was made on the basis of a preliminary knowledge of the modal shapes, obtained via the series of forced tests executed in the past, which made it possible to avoid the placement of the seismometers in the vicinity of a node.

In addition to the above described dynamic control system, a seismic monitoring system was also installed, to detected possible seismic motions affecting the structure and exceeding a predefined acceleration threshold.

The input motion exciting the structure was monitored at the dam base and on the two shoulders in order to gather data on amplifications, phase delay and coherence of the exciting motion; the structural response was measured at three different points. The location of the accelerometer is shown in fig. 3).

4. MATHEMATICAL MODELS

3D finite element models were set up for the interpretation of the data.

For the interpretation of the static behaviour, a mathematical model of the dam and the foundation was set up, assuming the following physical-mechanical characteristics for the materials:

- concrete:	
elastic module Ec	35000 MPa
Poisson's coefficient	0.2
- foundation:	
elastic module Er	Ec/3

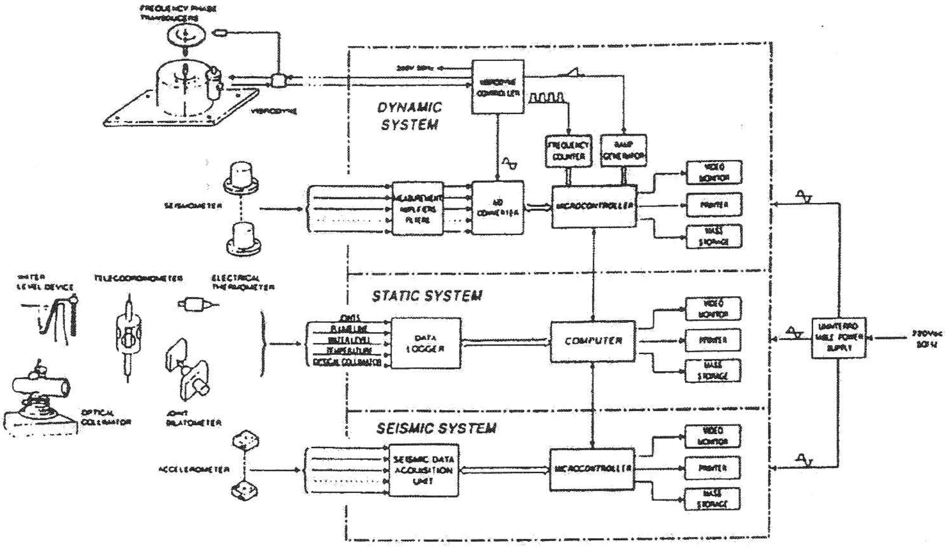


Figure 4. Talvacchia dam - monitoring system.

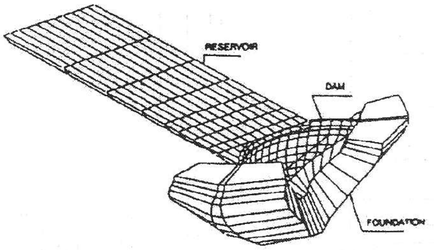


Figure 5. View of the dam-foundation-reservoir mesh.

Poisson's coefficient 0.2

On the basis of the results of the model, the relationships that tie the dam displacements with the reservoir level (hydrostatic component) and with the air temperature (thermal component) were derived through the use of "influence functions" and "mono-thermometric coefficients".

The model was then calibrated via comparison with the data collected over a number of years by the static surveillance system, obtaining a very good agreement between the measured and theoretical behaviour.

From the model used for the interpretation of the static behaviour, the 3D finite element model for the dynamic analyses was derived.

Several preliminary sensitivity analyses were carried out, to ascertain the reliability of the model and to evaluate the influence on the results of various parameters of the mathematical modelling.

The influence of the finite element discretization was examined by studying three cases with different number of elements of the mesh, and the discretization level beyond which the numerical results did not vary significantly was identified.

The influence of the Ec/Er ratio and of reservoir shape (planimetric shape, shape of the reservoir bottom, length of the modelled reservoir) were also examined.

The final adopted mesh is represented in fig. 5. The reservoir was reproduced with prismatic shape and length equal to three times the height of the dam, assuming the condition of entirely absorbent walls in correspondence to its free end.

The fluid was considered compressible and it was assumed that its motion has small displacements and speeds.

For the fluid the following characteristics were assumed:

- density 1000 kg/cu meter
- speed of sound 1440 m/sec.

The mathematical model was validated comparing the numerical results with the experimental values measured in "reference" forced vibrations tests performed in 1987 with a reservoir level equal to 80% of the maximum level.

In such "reference" tests, the dynamic response of the structure was measured in a number of points much larger than in standard tests automatically performed twice a day, and consequently a more detailed

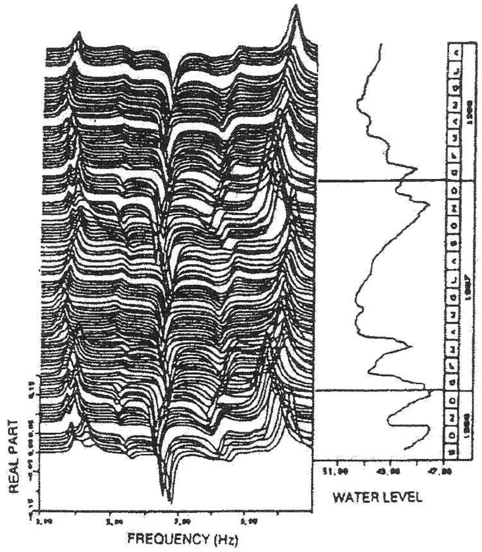


Figure 6. Example of real part of radial transfer functions and water level variations.

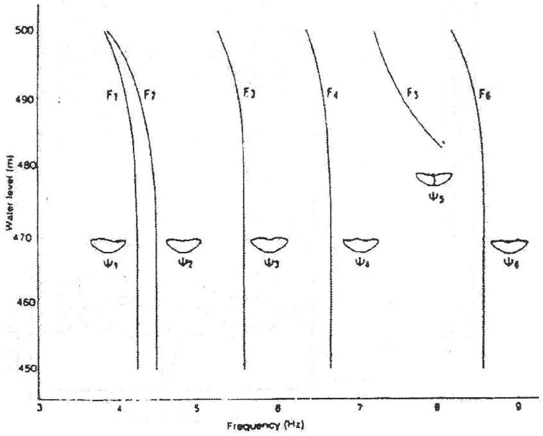


Figure 7. Natural frequency-water level influence functions.

description of the modal shapes of the structure was obtained.

The comparison between numerical and measured frequencies is shown in the next table.

Mode	Experimental frequencies (Hz)	Numerical frequencies (Hz)
1st	3.91	3.96
2nd	4.07	4.08
3rd	5.83	5.56
4th	6.80	6.63
5th	8.69	8.51
6th	10.44	10.55

5. EXPERIMENTAL RESULTS

The surveillance system has operated continuously since September 1986, except for a brief interruption of a few day for the replacement of a component.

With the execution of a static data acquisition every 6 hours and a forced tests every 12 hours, a large amount of information was gathered during the said period.

The results of the dynamic tests may be summarized, for each seismometer, in a series of response curves. By way an example, the real part of these curves for radial excitation, related to the central position, is presented in fig. 6. The same figure shows the water level time history, which certainly constitutes the parameter with the greatest influence on the natural frequencies of the system.

In the period under consideration, the examination of the experimental results showed that:

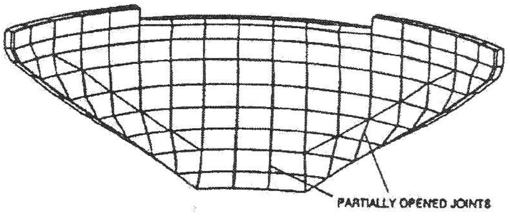
- in the 3 to 11 Hz frequency range 6 modes of the dam-reservoir system are present;
- the natural frequencies assume different values with the same reservoir level.

All this pointed out the fact that, besides the reservoir level, other quantities as well have a relevant bearing on the dynamic behaviour of the dam. In particular, the need of deeper investigation of the role played by the temperature variation and associated effects (such as variation in the contact conditions of the vertical joints). In this context, the interpretation of the phenomenon called for more sophisticated mathematical models.

6. INTERPRETATION OF THE RESULTS

Using the 3D finite element model, the theoretical fundamental frequencies were calculated for different water level conditions and "natural frequency-water level" influence functions were derived (see fig.7).

By means of such influence functions, it was possible to compare the measured variations in time of the natural frequencies with the corresponding theoretical ones. This comparison clearly confirmed that the measured variations can not be accurately reproduced taking into account only the influence of the water level.



·Figure 8. Mathematical model representing the opened joints condition

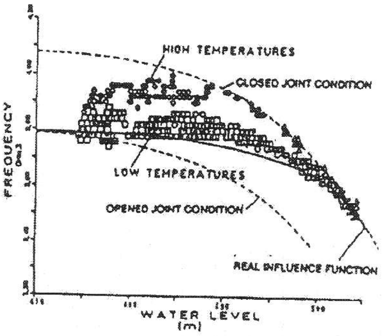


Figure 9. First mode frequencies versus water level.

As an example, fig. 9 puts in evidence that the measured values of the first fundamental frequency are well fitted by the theoretical influence function only for the highest water elevation, while for lower water elevations the experimental values are clearly influenced also by other factors.

Examining the measurements of the dilatometers positioned on the downstream face, a cyclic opening of the vertical joints was recognized, correlated with the ambient temperature variation.

Conditions of partially opened joints (resulting from the combined action of hydrostatic and thermal loads) were consequently reproduced in the mathematical model (see fig. 8) and their effects on the natural frequencies were computed. Several different "natural frequency-water level" influence functions were then set up, associated to different joints opening condition.

The measured values of the natural frequencies can range between the theoretical predictions derived for "closed joints" and "partially opened joints" conditions, depending on the actual variation in time of joints condition.

However, the theoretical results computed for partially opened joints, have a real meaning only for low water level; high water elevations, in fact produce a condition of "closed joints" for the structure, in any ambient temperature situation.

This interpretation allowed a very effective interpretation of the experimental results, as it is evident in fig. 9

A final theoretical prediction model was then set up, in which the measured water level and the joints opening were assumed as input data and the effects of these factors on the natural frequencies f were reproduced as:

$$f = f_{cl} \cdot i + f_{op} \cdot (1-i)$$

where f_{cl} and f_{op} are the frequencies calculated for closed and partially opened joints conditions, respectively, and i is an index (ranging form 0 to 1) of the water level (i=1 for maximum water level).

With this model a very accurate reproduction of the measured values on the entire period was obtained.